Ultrashort Pulse Propagation in Negative Index Materials: From Negative Refraction to Nonlinear Pulse Propagation

Michael Scalora, Mark J. Bloemer, and Charles M. Bowden
RDECOM, Aviation & Missile RDEC, AMSRD-AMR-WS-ID
Redstone Arsenal, AL 35898
Michael.Scalora@us.army.mil

Giuseppe D'Aguanno and Nadia Mattiucci
Time Domain Corporation, 6700 Odyssey Dr, Huntsville AL, 35806

Negative index materials (NIMs) hold the promise for super lensing of electromagnetic radiation for applications in radar, THz, and possibly at optical frequencies. We have developed a new vector pulse propagation method that we use to study the electrodynamics of negative index materials (NIMs). Although numerous papers have been published on the unusual properties of NIMs, we are the first to apply a propagation model to the problem. As we will show in the figures below, our propagation model provides added insight to the dynamics compared with the plane wave work published to date. In addition, the concept of index of refraction is not an explicit quantity found within Maxwell's field equations, and for this reason we resort only to the concepts of dielectric susceptibility ε and magnetic permeability μ. We thus numerically solve Maxwell's equations and show that a vector field indeed undergoes negative refraction (the beam is bent as if the index of refraction were negative) upon crossing an interface between vacuum and a medium where both ε and μ are negative and real, following a Drude model of both ε and μ {Fig.1}. On the other hand, we show that if the medium is thought of as a collection of Lorentz oscillators, then absorption completely destroys the process within a propagation depth of only a fraction of a wavelength {Fig.2}.

While quantities such as phase (V_p) and group (V_g) velocity, direction of propagation k and the index of refraction *n* are useful for uniform media, we caution that many of these quantities cease to be useful and may actually become misleading under extreme conditions, such as those that characterize NIMs. This is why we undertake the study of purely electromagnetic quantities, i.e., the fields **E** and **H**, and quantities associated with them, such as energy, flux, and electromagnetic momentum. Therefore we examine the relationship between the fields as they cross the interface and find interesting clues as to the reasons why the wave undergoes negative refraction. For example, for oblique incidence the transverse electric and magnetic fields remain in phase (continue to overlap as in free space), while the longitudinal magnetic field (i.e., magnetic field components that points in the direction of motion) is phase shifted, causing slight reflections and a rearrangement of the electromagnetic momentum and energy distribution that moves forward {Fig.3}.

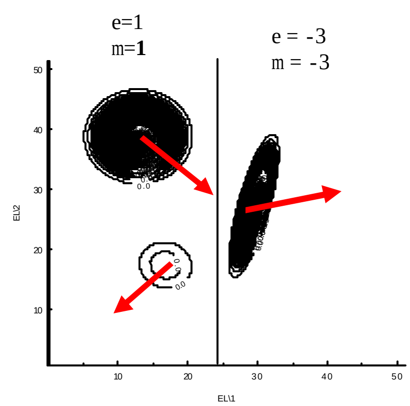

Fig. 1) A 20-fs pulse traverses a boundary that separates vacuum from a medium with ε=-3 and μ=-3. The beam is seen to refract in an unusual direction, while the transmitted energy and momentum reorganize into a distorted wave front.

We have also been studying layered NIM materials. We find that the dispersive properties of an etalon made of NIM are almost identical to the dispersive properties of a multilayer all-dielectric stack. This analogy results in a unique transmission spectrum, complete with pass band and band gaps and band edge resonances that can be used to exploit field localization phenomena. We have recently

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **00 DEC 2004**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Ultrashort Pulse Propagation in Negative Index Materials: From Negative Refraction to Nonlinear Pulse Propagation**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **RDECOM, Aviation & Missile RDEC, AMSRD-AMR-WS-ID Redstone Arsenal, AL 35898; Time Domain Corporation, 6700 Odyssey Dr, Huntsville AL, 35806**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001736, Proceedings for the Army Science Conference (24th) Held on 29 November - 2 December 2005 in Orlando, Florida. , The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**2**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

shown the existence of bright and dark gap solitons in a NIM etalon. Our approach to studying the fundamental quantities related to pulse propagation will hopefully reveal the unique potential for NIMs

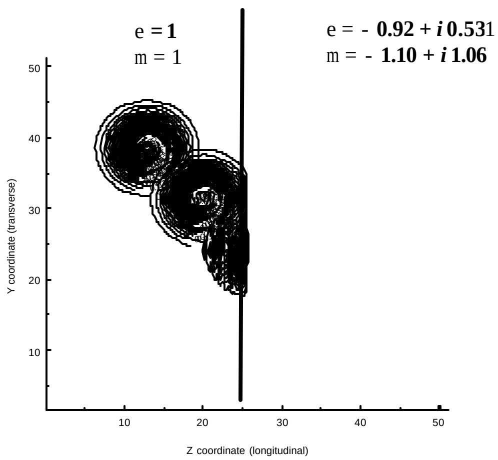

Fig.2. The same input pulse traversing a boundary that separates vacuum from a Lorentz-like medium, whose dielectric susceptibility and magnetic permeability are given by: ε=-0.92 + *i* 0.531 and μ=-1.10 + *i* 1.06 , respectively.

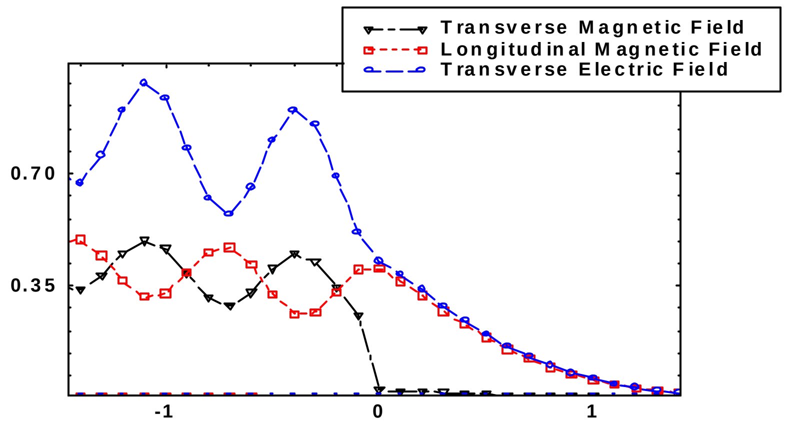

Fig.3. Snapshot of the transverse-electric and magnetic fields, and longitudinal magnetic field as they cross the interface for the interface of Fig.1. It is clear that this dynamics influences the Poynting vector and the energy distribution of the fields on both sides of the surface.